Research Laboratory
P. O. Box 1088
Schenectady, New York

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411.—CORONA LOSS AND RADIO INTERFERENCE MEASUREMENTS AT HIGH VOLTAGE A.C. ON TEST LINES IN SWEDEN

by N. KNUDSEN,

Chalmers University of Technology
(Sweden)

SUMMARY

On a test plant erected by the Swedish State Power Board in connection with the Chalmers University of Technology in Gothenburg comprehensive corona tests have been carried out during the last years. Beside the general intention to broaden the theoretical and practical knowledge about the corona phenomenon there has been a special purpose namely to compare the behaviour of double and triple conductors of the types used in Sweden which contain cables witch a diameter of 3,2 cm and a spacing of 45 cm.

The results of the experiment indicate that by use of triple conductors instead of double conductors the yearly losses, apart from ice losses, are reduced from about 1,4 kW/km to about 0,4 kW/km and the radio interference level is reduced by about 8 dB in fair weather, and probably somewhat more in bad weather. Expressed in another way the triple conductor has given approximately the same losses and radio disturbances at 460 kV as the double conductor at 400 kV.

Variations between 40 and 95 % in the humidity in the air did not seem to affect the losses nameworthly but a slight decrease in radio interference with increasing humidity was observed. Bad weather has given increasing losses in the following order: fog, dry snow, rain, wet snow, hoar frost.

A method for calculating fair weather losses is proposed and future work is outlined.

REPORT

INTRODUCTION

The first 400 kV lines built in Sweden are equipped witch double conductors consisting of two 593 mm² A.C.S.R. cables at a distance of 45 cm. Before the choice of the conductor type, experiments regarding corona losses and radio interference had been carried out on a test line at the Institute of High-Tension Research of Uppsala [1]. Later on, when the lines had been in operation for some time, field tests were undertaken, the results of which were substantially in agreement with the experiments [2].

In 1956 it was decided through an agreement between the Swedish State Power Board and the Chalmers University of Technology that a new test plant should be built in connection with the high voltage laboratory belonging to the university in order to carry out further investigations and thereby broaden

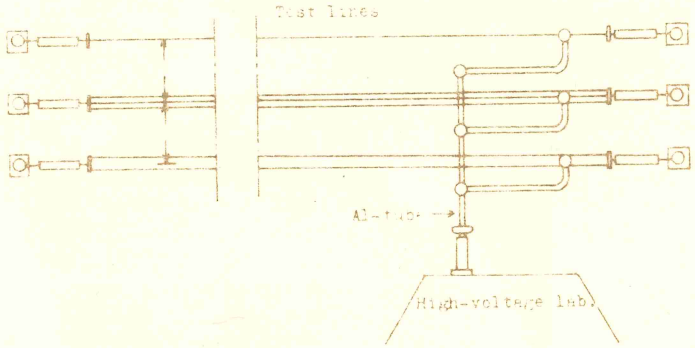

FIG. 1.—Test plant lay-out.

the theoretical and practical knowledge about the corona phenomenon [3]. One of the main reasons for this decision was that it was foreseen that in the future several 400 kV lines in this country should be equipped with conductors with three cables per phase and that it was of great importance to compare the behaviour of double and triple conductors with respect to corona.

Even single conductors have been tested but mainly with regard to D.C. performance. These tests have been described elsewhere [4] and are not delt with in this paper.

TEST PLANT AND MEASURING EQUIPMENT

The original lay-out, which comprises the lines used for A.C. (and partly also for D.C.) tests is shown in *figure* 1 and a view of the plant in *figure* 2. The lines have a length of 300 m and a mean height above ground of 13 m. The double and triple conductor contain Curlew cables (593 mm², r = 1,6 cm) with a spacing of 45 cm, used in the 400 kV lines in this country.

The various lines can be connected to a bus formed by an aluminium tube of 12 cm diameter mounted at 10 m height on stack insulators. Ordinarily only one conductor is connected

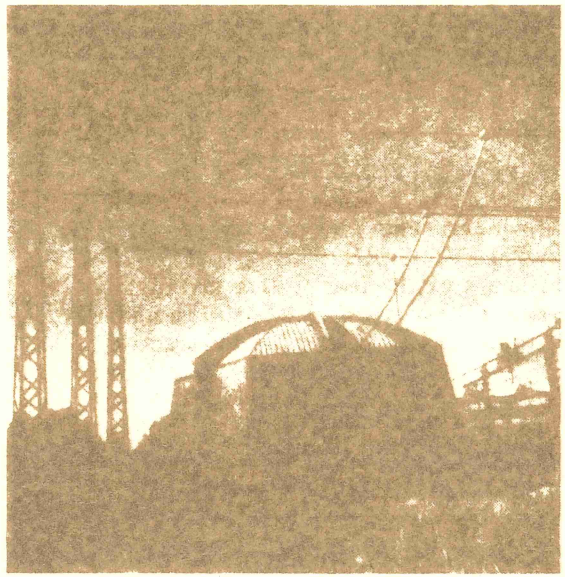

FIG. 2.—View of the test plant.

at a time, the other being free or earthed. For the connections between the bus and the lines and between the bus and the wall bushing leading into the high voltage laboratory flexible aluminium tubes are used. The system is fed from a high voltage single phase transformer rated 750 kV, 1 A.

As may be seen, the whole outdoor equipment is of a rather simple construction and as a consequence the total cost has been relatively low. As a cause of the short line length the insulator

and bus bar losses may at circumstances be relatively high and special precaution must be taken in order to eliminate them from the measuring results.

For measuring corona losses two different high-voltage bridges have been used. The one, which was first used, was of a special design constructed for the purpose (*fig.* 3). A part of the voltage

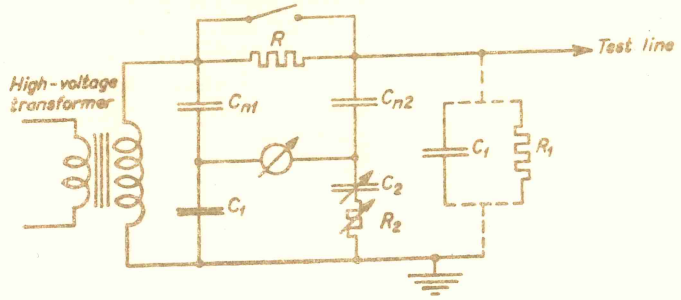

FIG. 3.—The first bridge used for corona loss measurements.

drop caused by the load current in the resistor R is transferred to the low voltage branches through two equal pressure-gas capacitors rated 500 kV, 50 pF.

The total losses of the test system are divided into line losses and bus losses. By measuring total losses and bus losses in turn the line losses are calculated as the difference

$$P_{line} = P_{total} - P_{bus}.$$

At the same time as the total losses are measured the line insulator losses which should be subtracted from the line losses are obtained by means of the arrangement shown in *figure* 4. The last element in the insulator chain, i. e. the element connected to ground, is shunted by a resistor R_{is}, which forms a branch in the measuring bridge. If the voltage drop in this resistor caused by the capacitive current in the insulator is compensated, the remaining voltage drop caused by the active current can be measured. This gives the active current, which multiplied with the line voltage, gives the insulator loss.

In spite of the fact that the bridge shown in *figure* 3 is quite adequate, the whole procedure is rather complicated and time-consuming. This is a disadvantage especially in wet weather, when the losses are altering every minute. For this reason another bridge method has been tried which directly gives the line corona losses without correction (*fig.* 5).

This bridge is in principle an ordinary Schering-bridge and the only special feature is that instead of using the total return current through earth, which would not be correct owing to stray capacitances in the transformer, only a part of the return current picked up by an antenna is fed to the one low voltage branch. As antenne is used one of the free parallel test lines. This seems to justify the assumption that the antenna current is in phase with the sum of the capacitive current and the corona loss current flowing into the line. The loss factor measured by the bridge should then be equal to the loss factor of the conductor at test.

Because in this way the results obtained by use of the Schering-bridge are based upon a physical assumption, which may involve an approximation, is has been necessary to check the results against those obtained by the first bridge. For this purpose a series of fair-weather tests were undertaken. On each of 11 days

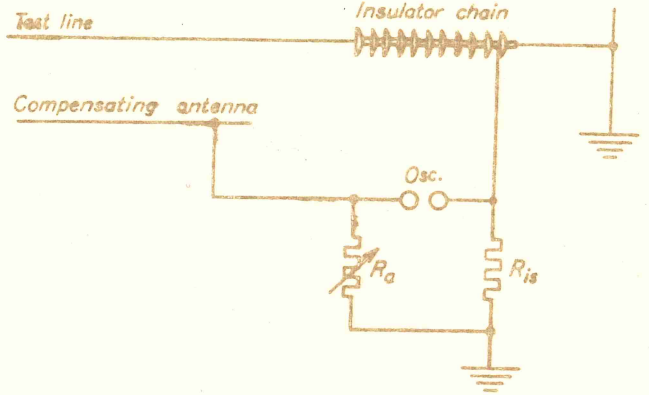

FIG. 4.—Arrangement for measuring of insulator losses.

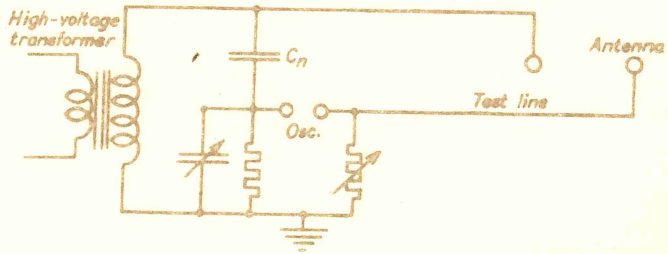

FIG. 5.—Schering-bridge for corona loss measurements.

the double conductor was tested at 300 kV by means of both bridges, the time interval between two comparative tests being at most a few hours. The result is given in *figure* 6.

If the two methods had given each day the same result—but of course somewhat different results from one day to the other—the eleven points in the figure would have been located on a straight line through origo with a slope of 45°. Instead the points are scattered around a line inclined 0,85 : 1 in relation to the abscissa. This means that the Schering-bridge has given in average 15 % lower values than the first bridge. The fact that the scattering in the direction of the mean line is greater than the scattering in the direction perpendicular to the line indicates that the variation is for the most part due to varying weather and test line conditions and only to a less degree due to inaccuracy in the setting of the bridge.

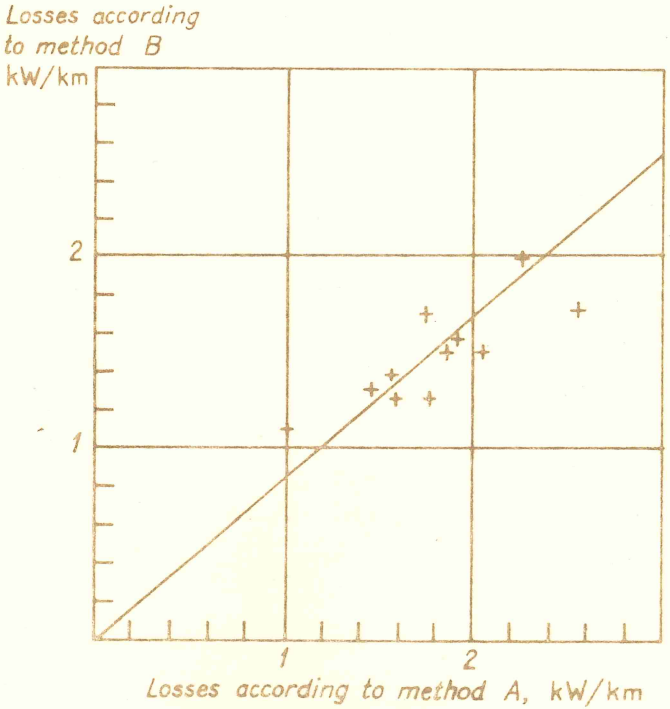

FIG. 6.—Comparison between results of corona loss measurements obtained by the two different methods. A. Method according to *figure* 3. B. Method according to *figure* 5.

The fact that the Schering-bridge here gives loss values which the variation in the coupling between the test line and the antenna seem to be somewhat too low, may partly be explained through in the middle of the span, where the losses are maximum on account the lower height, the coupling is minimum. In this way at least 5 % the 15 % deviation may be explained.

In judging the result shown in *figure* 6 it must be remembered corona, such as it appears on high voltage lines, in practice is

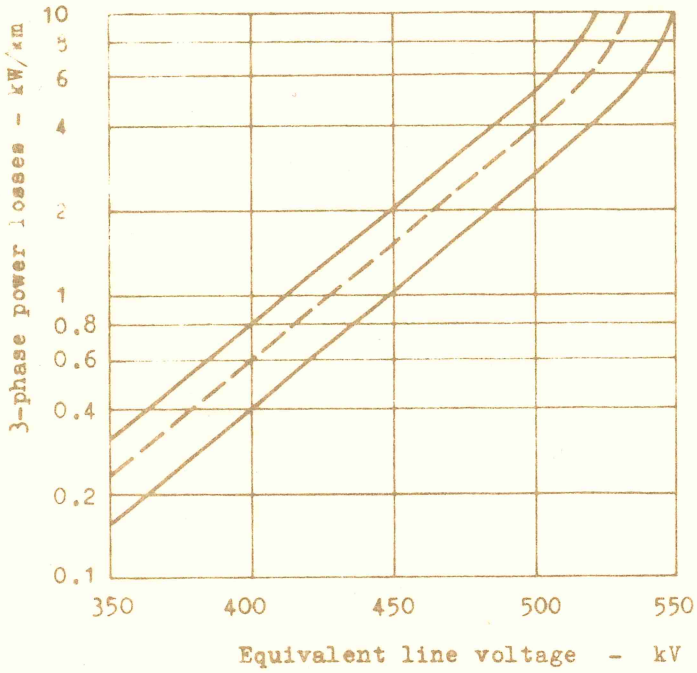

FIG. 7.—Boundary loss curves and mean loss curve from 15 voltage run tests in fair weather. Double conductor was used and temperature was between 6 °C and 26 °C. Tests carried out on various days from March 17, 1959 to July 8, 1959.

to a certain degree a statistical phenomenon. This is true as well with regard to the suberitical fair-weather corona as with regard to the more heavy corona caused by wet and icy conductors. Experience shows that fair-weather losses measured on a certain line may vary within a range of 1 : 2 or more. Further the relation between bad-weather and fair-weather losses of the same line and the same voltage may vary within a range of about

100:1 or in other words with 10 000 %. With these facts in mind the above result seems to be quite tolerable.

The measurements of radio interference have been made by means of a standard apparatus, the STMG 3800 constructed by Siemens which complies with the demands of C.I.S.P.R. The apparatus is placed under the midpoint of the conductor which is insulated with regard to high frequency voltages and currents from the bus by means of a choke coil. By this arrangement the variation of the noise with frequency shows a very pronounced but well defined pattern of peaks and valleys as a cause of the reflections of the waves at the line ends.

RESULTS OF LOSS MEASUREMENTS

Typical results from test series in fair weather and in rain are given in *figures* 7 to 10. In fair weather the voltage was varied in relatively small steps as it showed that the losses for each voltage level could be determined practically instantly and independent of the preceding voltage level. When the losses were plotted in a logaritmic scale as a function of voltage the curves from the various test series were nearly straight-lined apart from the region, where the critical voltage was approached (only in *fig.* 7).

The voltage values in these figures are not the actual test voltages but such equivalent line voltages, which on a Swedish 400 kV line of the normal flat configuration would give the same nominal voltage gradient on the cable surface. This means that

$$V_{line} = \sqrt{3}\, V_{phase}$$

and

$$V_{phase} \times c_{phase} = V_{test} \times c_{test} = E\,\frac{nr}{18}$$

where c denotes capacitance in μF/km, E voltage gradient in kV/cm, n number of cables in the conductor and r radius of the cable in cm.

For the double conductor we have

$$c_{phase} = 0{,}00115\ \mu F/km,$$

and for the triple conductor

$$c_{phase} = 0{,}00129\ \mu F/km.$$

Corresponding to the normal line voltage 400 kV the voltage gradient is found to be

$$E = 15\ kV/cm$$

and

$$E = 11{,}2\ kV/cm$$

for the double and the triple conductor respectively, which values may be used, when comparing the results related here with results from other tests.

The following comments could be applied to *figures* 7 and 8.

1. The maximum deviation from the mean line is of order ± 30 %. About half of this seems to be due to variations in

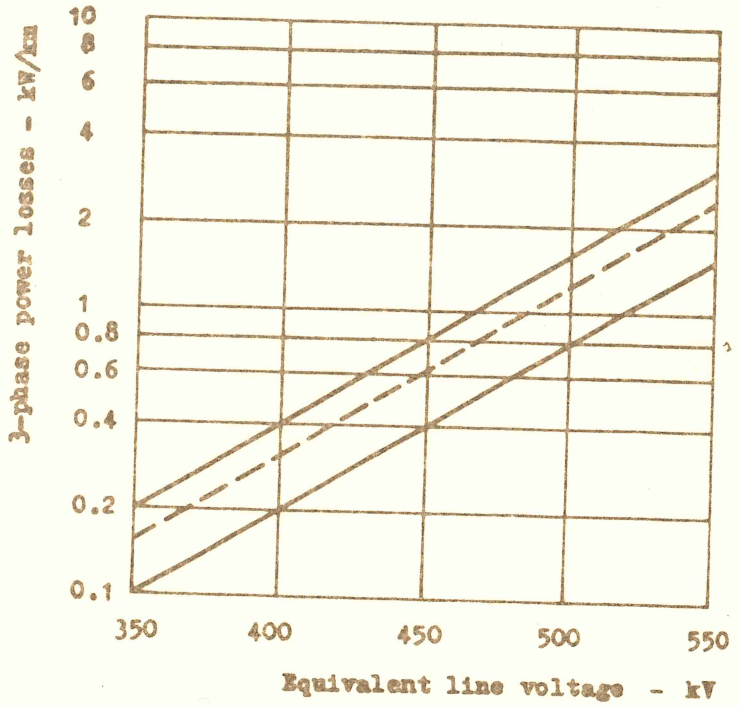

FIG. 8.—Boundary loss curves and mean loss curve from 15 voltage run tests in fair weather. Triple conductor was used and temperature was between 6 °C and 26 °C.

the air density, which was made evident by shifting the voltage scale in relation to this quantity.

2. Well below the critical voltage the power losses are doubled when the voltage is increased by 40 kV in the case of the double conductor and by 50 kV in the case of the triple conductor. Expressed in a more general way this means that the losses are doubled when the voltage is increased by 10 % of that line voltage which

correspond to a nominal field gradient of 15 kV/cm. This rule may perhaps be used for precalculation of corona losses in fair weather as will be shown in the following.

3. The loss per cable in the triple conductor equals the loss per cable in the double conductor at a 20 % higher voltage on the triple conductor. That a still better result is not obtained by use of triple conductor shows that the loss per cable is not

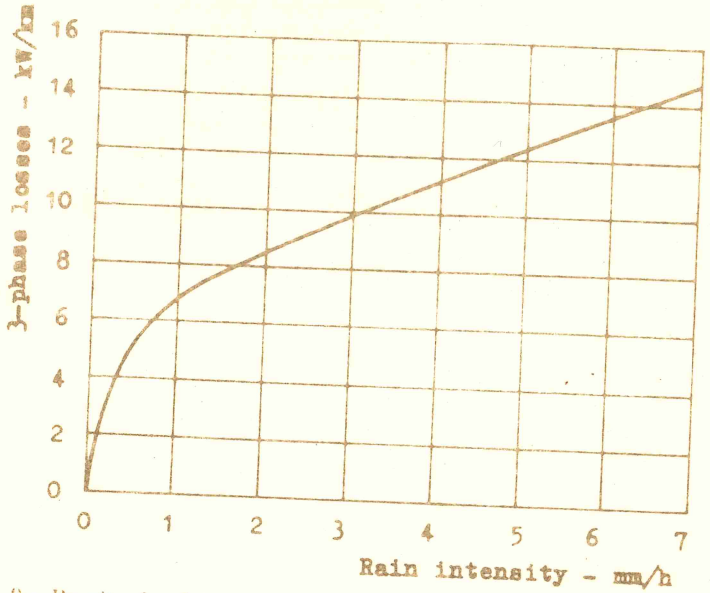

FIG. 9.—Result of rain test with double conductor exposed to a voltage corresponding to 400 kV.

only defined by the voltage gradient but also to a certain extent by the voltage itself. It may also be that there are other explanations, for instance that the triple conductor as a cause of the low gradient was less "trained" than the double conductor.

4. The relative humidity did not seem to have any influence at all on the losses. This was made evident by means of a special test series including 20 tests on various days with the relative humidity varying between 40 % and 95 %.

Regarding the result of the measurements in rain the following may be said.

The typical saturation knee in the curve in *figure* 9 and in the two upper curves in *figure* 10 is probably due to space

charges. This phenomenon is not observed in the lower curve in *figure* 10, which relates to 400 kV on a line with triple conductors. The explanation may perhaps be that in this case because of the low voltage gradient heavy discharges only occur on water drops, when they strike on or leave the conductor and not on hanging drops. The improvement by use of a triple conductor instead of a double conductor is here very remarkable.

Among other results of bad weather conditions it may be mentioned that fog and dry snow gave rise to losses about three times as great as in fair weather and that wet snow and hoar frost gave very heavy losses of about 40 to 60 kW/km at normal voltage on the double conductor.

CALCULATION OF ALL-WEATHER LOSSES

The yearly corona losses on a line can be estimated with more or less accuracy. The most simple way is to apply an empirical factor to the fair weather losses. However, this figure will depend not only on the climatic conditions but also on the line data,

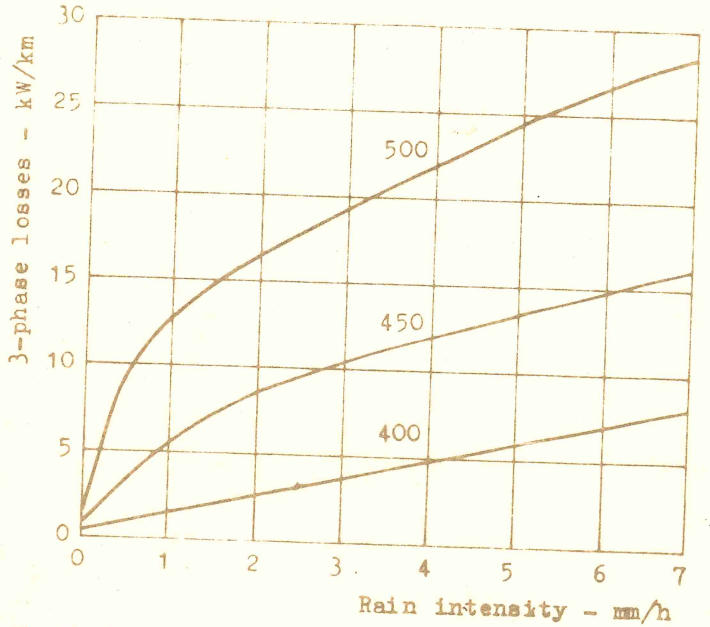

FIG. 10.—Results of rain tests with triple conductor at three voltage levels corresponding to 400, 450 and 500 kV line voltage.

which may be seen from [5], where values between 1,66 and 5 are found. Even higher and lower values are found in the literature.

A generally used method is to calculate the mean loss during a year by means of an expression of the following kind

$$P_{mean} = t_1P_{fair} + t_2P_{fog} + t_3P_{rain} + t_4P_{snow} + t_5P_{ice}$$

where t_1, t_2, etc., denote the relative durations of the various weather types.

Amongst the above terms the last one is probably the one, which is determined with the least accuracy. With regard to the lines in the northern parts of Sweden this may introduce a special uncertainty in the calculation.

For the southern parts of Sweden the term can probably be neglected.

As dry snow gives lower losses and wet snow higher losses than rain, it seems reasonable to put

$$P_{snow} = P_{rain}$$

and add t_4 to t_3.

Let us—mainly as an example—assume that we for the climate in the middle and southern parts of this country can calculate with

$$\begin{aligned} t_1 &= 0{,}80 \\ t_2 &= 0{,}05 \\ t_3 + t_4 &= 0{,}15 \\ t_5 &= 0. \end{aligned}$$

The number of rain and snow hours per year should be about 1 300. The yearly precipitation is of order 600-700 mm in mean. Accordingly the mean rate of rainfall (snowfall) is about 0,5 mm/h. If we now assume that the corresponding loss figures taken from *figures* 9 and 10 can be regarded as representative, which is most sure in the case of the triple conductor because the 400 kV curve in *figure* 10 is practically straight-line shaped we find

$$\begin{aligned} P_{rain} &= 5{,}2 \text{ for the double conductor,} \\ P_{rain} &= 0{,}9 \text{ for the triple conductor.} \end{aligned}$$

Now there only remains to fix the fog losses. Let us assume that they are three times as great as the fair weather losses. We then have for the double conductor

$$P_{mean} = 0{,}80 \times 0{,}6 + 0{,}05 \times 1{,}8 + 0{,}15 \times 5{,}2 = 1{,}35 \text{ kW/km}$$

and for the triple conductor

$$P_{mean} = 0{,}80 \times 0{,}3 + 0{,}05 \times 0{,}9 + 0{,}15 \times 0{,}9 = 0{,}42.$$

The relation between mean losses and fair weather losses should then be

$$\begin{aligned} P_{mean}/P_{fair} &= 2{,}3 \text{ for the double conductor,} \\ P_{mean}/P_{fair} &= 1{,}4 \text{ for the triple conductor.} \end{aligned}$$

The gain in form of reduced losses by use of triple conductors instead of double conductors is mainly obtained during bad weather conditions. While the losses in fair weather are reduced in proportion 2 to 1 they are at light rain reduced in proportion 6 to 1.

RADIO INTERFERENCE MEASUREMENTS

In order to obtain a well defined frequency spectrum the field intensity meter was placed directly beneath the middle point of the test line, which was shielded from the bus bar by an inductive coil. By measuring over a wide frequency range curves like the one shown in *figure* 11 could be drawn, which curves were essentially of the same shape for various tests. With the well-known

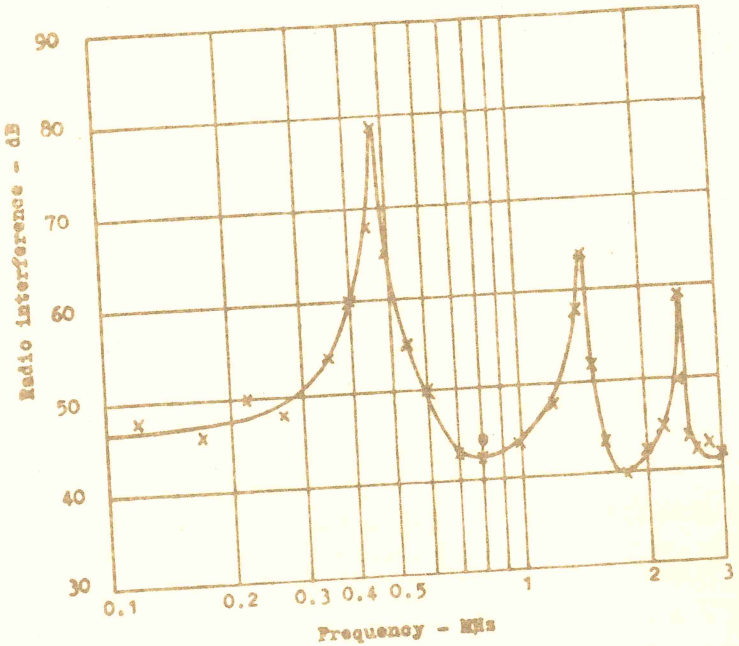

FIG. 11.—Typical frequency spectrum of 300 m test line.

fact in mind that the interference from an infinite line can be represented by a mean curve it was later on possible to restrict the measurements to one or a few frequencies and apply the appropriate corrections taken from representative wide range tests.

Typical results from measurements in fair weather are shown in *figure* 12. Each point in the figure is the mean value from 24 different tests on various days. The 24 individual values were originally plotted against the relative humidity, whereby it was found that although the scattering was rather great there was a clear tendency, that the interference level decreased with

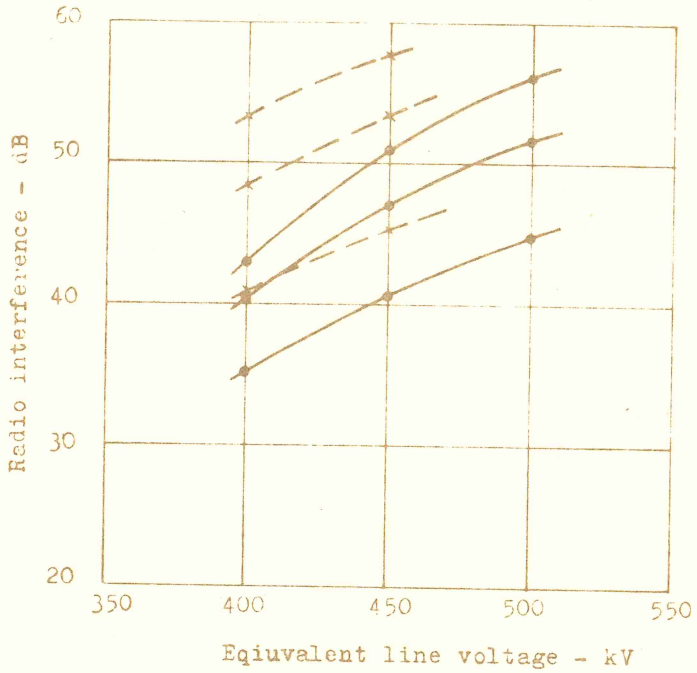

FIG. 12.—The three dotted curves give in downward direction the radio interference level for the double conductor at 0,2, 1 and 3 MHz. The full curves give correspondingly the losses of the triple conductor.

increasing humidity. Thus when the humidity varied within the range 45-95 % the disturbance level decreased about 2 or 3 dB.

It may be noted that the greatest improvement by use of triple conductor instead of double conductor occur at the lower frequency 0,2 MHz at 400 kV and is about 10 dB. At 3 MHz the

improvement is 6 dB. The triple conductor shows the same level at 460 kV as the double conductor at 400 kV.

Only a few measurements in rain have hitherto been made. They have indicated an increase in noise level about 5 to 10 dB. The increase is higher for the double conductor than for the triple conductor.

DISCUSSION OF FAIR WEATHER LOSSES. FUTURE WORK

It is often thought that the fair-weater corona is a phenomenon of a pronounced random nature being caused by irregularities along the conductor surface. Whatever this is true or not it may be said, that our general impression from numerous loss measurement during more years is that the constancy and reproductivity of the fair weather losses has not been bad. Moreover, the shape and the slope of the curves shown in *figure* 1 and 2 is in good agreement with the mean curve from a great number of investigations carried out in seven countries [6].

A special study [7] has shown that a precalculation of fair-weather losses may be carried out as follows:

1. Estimate the corona losses at normal air density and at the nominal surface gradient 15 kV/cm by means of the rule

$$P_{15} = n^2 r^2 P_{15u}$$

where P_{15u} is the value of P_{15} for unit values of n and r i. e. for a single conductor with a radius of 1 cm. According to tests in various parts of Sweden P_{15u} is of order 0,06 kW/km or perhaps about 0,08 if corrections are made with regard to air density. According to the above mentioned tests in other countries it is of order 0,12 kW/km. Select one of these values or an intermediate value. If reliable tests have been carried out under conditions which are somewhat similar to the actual case select a value, which used in the following calculations gives a result in accordance with such tests.

2. Calculate by means of the expression

$$V = \sqrt{3}\, E \frac{nr}{18c},$$

where c is the line capacitance in μF/km either the voltage V_{15} which corresponds to the nominal surface gradient 15 kV/cm or the gradient E which corresponds to the actual voltage V and thereafter the radio

$$v = \frac{V}{V_{15}} = \frac{E}{15}.$$

3. Calculate the line losses at normal air density by means of the formula

$$P = P_{15} 2^{2\delta} \cdot v - 1,$$

This may be carried out arithmetically or graphically. In the latter case one may take advantage of the following approximation

$$\log 2 = 0{,}3010 \simeq 0{,}3$$

which implies that at $E = 20$ and correspondingly

$$v = \frac{20}{15} = \frac{4}{3}$$

we have

$$\frac{P_{20}}{P_{15}} = 2^{\frac{10}{3}} \simeq 10$$

Using the voltage gradient for the abscissa a logarithmic graph is very simple and easily made as shown in *figure* 13.

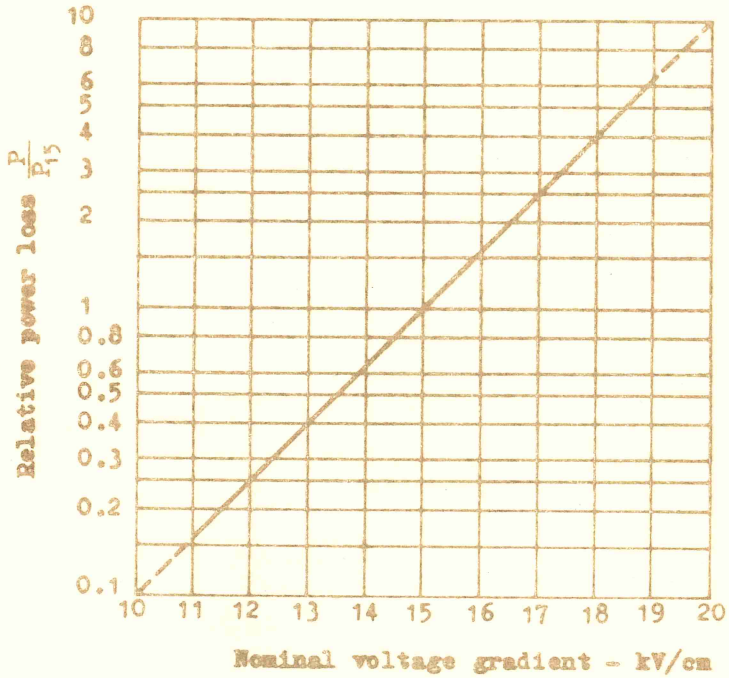

FIG. 13.—The relative power loss P/P_{15} as a function of the nominal voltage gradient. Note that the linear (or in fact exponential) relationship is considered to be most close within the range 11-19 kV/cm.

4. If a correction for air density is needed the relative air density δ should in a first approximation enter in the above expression for P in the following way

$$P = P_{15} 2^{2\delta} \left(\frac{v}{\delta} - 1\right)$$

which implies a scale shift in voltage. If δ is increased from 1 to 1,01 i. e. with 1 %, the result will be a decrease of P with 7 %.

With regard to future work it may be mentioned that during August 1963 three new conductors have been installed. It is the intention to study in first hand:

1. Influence of drawing and ageing of cables.
2. Reproductivity of fair weather losses and radio interference.
3. Influence of bad weather in order to get more information about losses as well as radio interference.
4. Behaviour of single and double conductors at D.C. voltage.

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